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Aeronautical composite/metal bolted joint and its mechanical properties: a review

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Abstract

Purpose – Bolted joint is the most important connection method in aircraft composite/metal stacked connections due to its large load transfer capacity and high manufacturing reliability. Aircraft components are subjected to complex hybrid variable loads during service, and the mechanical properties of composite/metal bolted joint directly affect the overall safety of aircraft structures. Research on composite/metal bolted joint and their mechanical properties has also become a topic of general interests. This article reviews the current research status of aeronautical composite/metal bolted joint and its mechanical properties and looks forward to future research directions.

Design/methodology/approach – This article reviews the research progress on static strength failure and fatigue failure of composite/metal bolted joint, focusing on exploring failure analysis and prediction methods from the perspective of the theoretical models. At the same time, the influence and correlation mechanism of hole-making quality and assembly accuracy on the mechanical properties of their connections are summarized from the hole-making processes and damage of composite/metal stacked structures.

Findings – The progressive damage analysis method can accurately analyze and predict the static strength failure of composite/metal stacked bolted joint structures by establishing a stress analysis model combined with composite material performance degradation schemes and failure criteria. The use of mature metal material fatigue cumulative damage models and composite material fatigue progressive damage analysis methods can effectively predict the fatigue of composite/metal bolted joints. The geometric errors such as aperture accuracy and holes perpendicularity have the most significant impact on the connection performance, and their mechanical responses mainly include ultimate strength, bearing stiffness, secondary bending effect and fatigue life.

Research limitations/implications – Current research on the theoretical prediction of the mechanical properties of composite/metal bolted joints is mainly based on ideal fits with no gaps or uniform gaps in the thickness direction, without considering the hole shape characteristics generated by stacked drilling. At the same time, the service performance evaluation of composite/metal stacked bolted joints structures is currently limited to static strength and fatigue failure tests of the sample-level components and needs to be improved and

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verified in higher complexity structures. At the same time, it also needs to be extended to the mechanical performance research under more complex forms of the external loads in more environments.

Originality/value – The mechanical performance of the connection structure directly affects the overall structural safety of the aircraft. Many scholars actively explore the theoretical prediction methods for static strength and fatigue failure of composite/metal bolted joints as well as the impact of hole-making accuracy on their mechanical properties. This article provides an original overview of the current research status of aeronautical composite/metal bolted joint and its mechanical properties, with a focus on exploring the failure analysis and prediction methods from the perspective of theoretical models for static strength and fatigue failure of composite/metal bolt joints and looks forward to future research directions.

Keywords Composite/metal stacks, Bolted joint, Prediction model, Mechanical properties

Paper type Literature review

1. Introduction

The application of largescale integrated manufacturing technology for composite materials has greatly reduced the number of aircraft components. However, due to various requirements for design, process, maintenance and transportation, a large number of design separation surfaces and process separation surfaces still exist widely between composite/composite and composite/metal parts (Chang *et al.*, 2010). The existence of transition joining zones between composite/composite and composite/metal disrupts the integrity of the overall structure and introduces significant stress concentration. The joint area has become an important link in the design and manufacturing of large aircraft (Zuo, 2018; An *et al.*, 2024).

The typical joint methods currently applicable to composite materials mainly include mechanical joint, adhesive joint, suture joint, Z-pin joint and hybrid joint methods. The schematic diagrams of various connection methods are shown in Figure 1. Mechanical joint is a method of connecting fasteners such as bolts and rivets through assembly holes. Its advantages are high connection reliability, large load transfer and no thickness limitation and its disadvantages are obvious stress concentration and improper selection of fasteners may cause electrical corrosion (Zuo *et al.*, 2020). Adhesive joint is made through adhesive, which has the advantages of light weight and no corrosion issues and has the disadvantages of limited load transfer capacity, nondisassembly and difficult to check the bonding quality (Kupski and Teixeira, 2021). Suture joint (Cao, 2007) and Z-pin joint (Zhou *et al.*, 2022; Zhang *et al.*, 2021a, b) are the two typical auxiliary joint methods, usually used in conjunction with other joint methods. They use the *Z*-direction dense penetration auxiliary joint method to improve the peeling strength and ultimate safety performance of the joint. Hybrid joint is a combination of the multiple connection methods, among which the most common is the adhesive/screw hybrid joint (Zhang *et al.*, 2021a, b; Liu *et al.*, 2023), which not only combines the advantages of two joint methods but also introduces the disadvantages of the two joint methods to a certain extent.

In addition, some scholars have also explored the application of welding joint technology using ultrasound and laser as heat sources in thermoplastic composite/thermoplastic

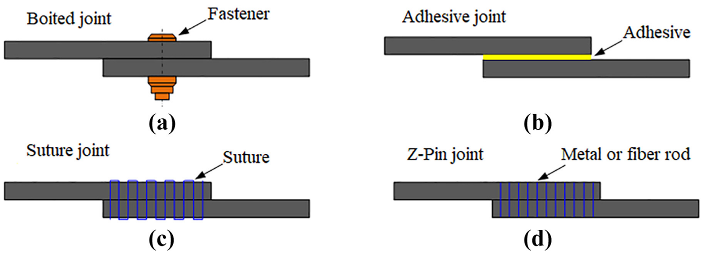

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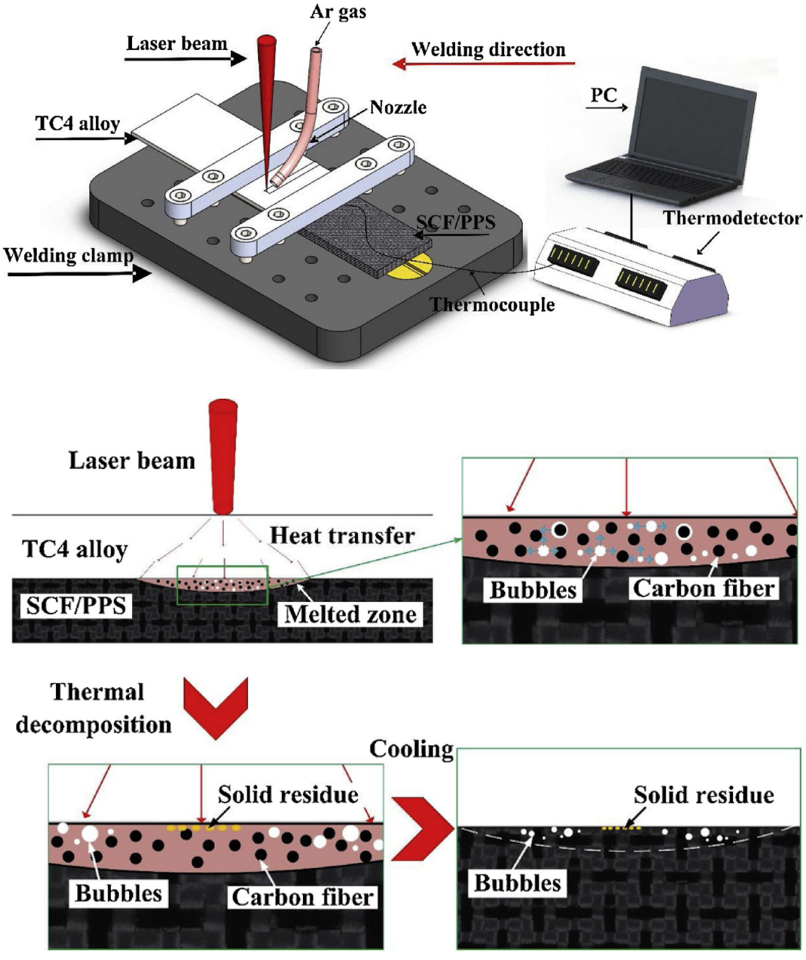
Figure 1.
Typical joint methods for composite material

composite and thermoplastic composite/metal joints, as shown in Figure 2 (Tao *et al.*, 2019; Kashaev *et al.*, 2015). However, due to the fact that the composite used in important structural components of aircraft are usually thermosetting composite materials with better comprehensive mechanical properties, such as the T800/X850 CFRP commonly used in aircraft, which has a glass transition temperature of only about 180 ℃ (Xu *et al.*, 2018), the mechanical properties will undergo irreversible degradation and do not have the ability to rebond when heated to higher temperature, Therefore, the welding joint technology of composite/metals is difficult to apply to the aviation industry.

Mechanical joint is the most important joint method in aircraft composite/metal stacked joint due to its larger load transfer capacity and higher manufacturing reliability (Jia *et al.*, 2015; Dong *et al.*, 2015; Kelly, 2006; Wang *et al.*, 2018). It is mainly divided into two types: bolted joint and rivet joint. The rivet joint can easily cause damage to the hole edge due to crushing. At the same time, it is difficult to maintain consistency and stability in the clamping torque during manual riveting, and it is only used in some thin nonload-bearing joint



Source(s): Tao *et al.* (2019)

Figure 2.
Experimental setup and principle for laser welding of composite to the titanium alloy

structures. Bolted joints have the advantages of strong load-bearing capacity, high reliability and a certain degree of disassembly, which is the most important type of joint in composite/metal stacked structures and the most widely studied mechanical connection in composite/metal stacked structures.

During the mechanical joint process, due to significant stress concentration, each connection hole is a potential source of failure (Wang *et al.*, 2020), and the composite/metal stacked mechanical joint part is also a weak link in the overall structure. Aircraft components are subjected to complex hybrid variable loads during service (Wang *et al.*, 2023), which places high demands on the mechanical properties of composite/metal stacked structures. According to the statistics, 75% of body failures occur at the joint position (Wei *et al.*, 2009), so the quality of mechanical joints directly determines the mechanical performance of the overall structure. The mechanical joint problem of composite materials is an important issue in the design and manufacturing of advanced aircraft, which restricts the largescale application of composite materials in aircraft. In order to maintain and enhance Europe's sustained competitiveness in the field of aircraft manufacturing, the European Union has been continuously funding programs such as Bolted Joints in Composite Aircraft Structures (BOJCAS) since 2000, to solve the problem of composite/composite and composite/metal joints in aircraft structures (McCarthy, 2001). The research on composite/metal mechanical joints and their mechanical properties has also received widespread attention from scholars.

This article comprehensively reviews the research progress on static strength failure and fatigue failure of composite/metal mechanical joints and summarizes its impact and correlation mechanism on the mechanical properties of connections from the aspects of hole-making quality and assembly accuracy of composite/metal stacked structures. The urgent challenges in the mechanical joint of composite/metal stacked structures were pointed out, and further research directions for the mechanical joint of composite/metal stacked structures were prospected.

2. Static strength failure of composite/metal bolted joints

Static strength failure refers to the failure phenomenon of a structure where the static or quasi-static stress exceeds the limit it can withstand under the action of static or quasi-static forces, resulting in fracture and other failures. A typical composite/metal bolted joint unit can be considered as a multiphase mechanical system composed of composite components, metal components and bolts (Shan *et al.*, 2020). The overall failure of the connection structure is closely related to the failure mechanism of each component (Liu *et al.*, 2021). The damage and failure situation of metal materials in composite/metal bolted joints is usually better than that of composite materials under static load, because metal materials usually have good plasticity while fiber reinforced composite materials have almost no plasticity and exhibit brittleness before failure occurs. The common failure mechanism of elastic-plastic metals is relatively clear, entering the plastic stage after the online elastic stage and then experiencing fracture failure. Composite materials have almost no plasticity, resulting in more significant stress concentration. As shown in Figure 3, the basic failure mechanisms of composite materials in bolted joint structures can be summarized as extrusion failure, tensile failure, shear failure and combined failure modes. The tensile failure of the net section is related to the tensile failure of the fiber/matrix caused by tensile stress, and the main reason for the failure is that the connecting section does not have sufficient strength to bear the tensile stress of the bolt. Shear failure is the opposite of tensile failure. The section can withstand tensile stress but the edge of the hole cannot bear higher shear stress, leading to the occurrence of shear failure. Extrusion failure is considered a relatively safe form of failure (Zhang *et al.*, 2020a, b), which is caused by high circumferential compressive stress. The failure process develops relatively slowly and can be detected timely during daily maintenance, making it less likely to cause catastrophic

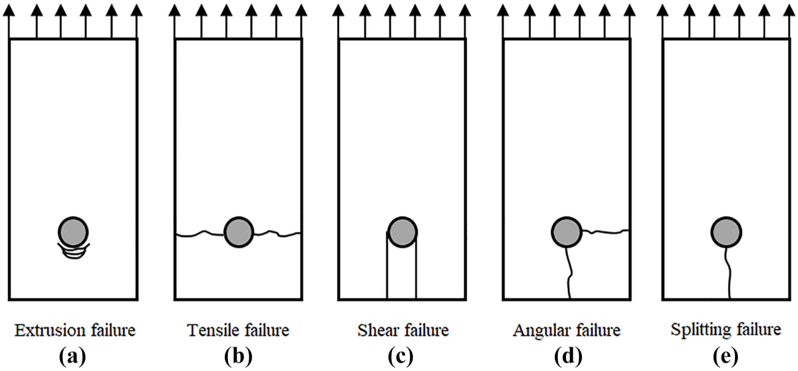


Figure 3. Failure mode of composite material in bolted joint

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accidents. Therefore, in the design of composite/metal stacks bolted joints, composite material extrusion failure is a common form of target design failure. In composite/metal bolted joint structures, there are multiple combined failure modes of composite materials, such as angular failure caused by tensile and shear combinations. In addition, when the selection of fasteners is inappropriate or the material performance of the fasteners is poor, pull-off and shear failure of fasteners in the connection structure are also common forms of failure.

The research on the static strength failure of composite/metal bolted joints includes two aspects: experimental and theoretical research. In terms of testing, a material mechanical performance testing machine is mainly used to conduct static strength tensile tests on the connection structure. In recent years, extensive research has been conducted on the static strength failure characteristics of composite/metal bolted joint structures with different forms and materials. Table 1 summarizes the basic information and experimental results of materials and structures in each study, and it can be seen that extrusion failure of composite materials is the most important form of failure. In addition, shear failure may occur when the edge distance of some holes is small, and fracture failure of fasteners may occur because the poor strength of fasteners.

In terms of the theoretical research, due to the differences in static strength failure characteristics between composite and metal materials, the research on static strength failure of bolted joint structures mainly focuses on the failure prediction and analysis methods of

Table 1. Static strength failure mode of composite/metal bolted joint

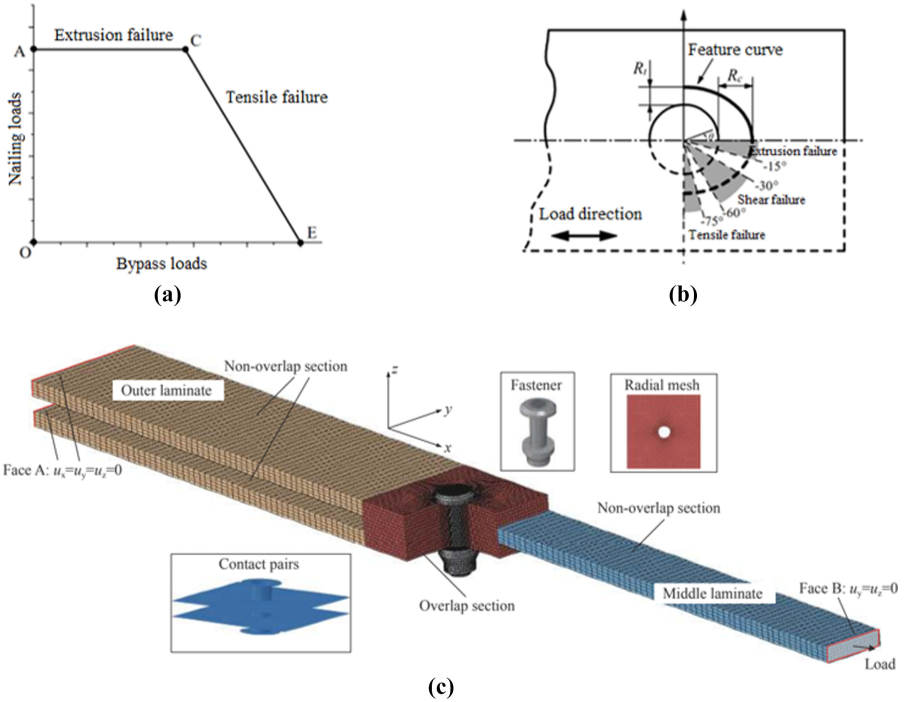
Researcher	Composite	Metal	Joint	Failure mode
Zuo (2018)	T800/X850 3.384 mm	Ti6Al4V 3.4 mm*2	Single nail and single shear	Extrusion and shear failure
Cao *et al.* (2018)	T800/X850 3.384 mm	Ti6Al4V 3.9 mm*2	Single nail double shear	Extrusion failure
Liu *et al.* (2013b)	CYCOM977 3.8 mm	Ti6Al4V 2 mm	Double nail single shear	Extrusion failure
Li *et al.* (2019)	T700 3.2 mm	Al7075 3 mm	Single nail and single shear	Extrusion and shear failure
Kweon (2019)	USN125 1.5 mm*2	7075-T62 3.224 mm	Single nail double shear	Extrusion failure
Gui *et al.* (2021)	Composite	Aluminum alloy	Multiple nails and single scissors	Extrusion failure

Source(s): Table created by authors

composite static strength, including the strength envelope method, feature size method and progressive damage analysis theory, as shown in Figure 4. The strength envelope method was proposed by Hart Smith (1976), which mainly determines the position of key points on the envelope line through experiments and other methods to determine the empirical model. Because the characteristics of simple and fast, the strength envelope method has been widely used in engineering. Over the years, scholars have continuously proposed various correction methods to improve its accuracy, such as Liu *et al.* 's (2013a) modified strength envelope method considering bypass loads. However, the strength envelope method is essentially an empirical model that does not consider the anisotropy of composite materials, which requires a large amount of testing and is difficult to effectively transfer and apply in structures with different stacked schemes.

The feature size method is an empirical model based on linear elastic fracture mechanics, proposed by Whitney and Nuismer (1974). The feature size method is used to determine the failure state of bolted joints structures by the failure state at a certain size of point from the holes edge. The classic feature curve method proposed by Chang *et al.* (1982) is shown in equation (1), which shows that the key parameters of the feature curve are compression feature size and tensile feature size, and the failure mode is related to θ angle dependent, when $0° \leq |\theta| \leq 15°$, the failure criterion is extrusion failure, when $30° \leq |\theta| \leq 60°$, the failure criterion is shear failure and when $75° \leq |\theta| \leq 90°$, the failure criterion is tensile failure.

$$r_c(\theta) = r_0 + R_t + (R_c - R_t)\cos(\theta) \quad -90° \leq \theta \leq 90° \tag{1}$$



(a)

(b)

(c)

Source(s): Hart-Smith (1976) and Liu *et al.* (2013a, b)

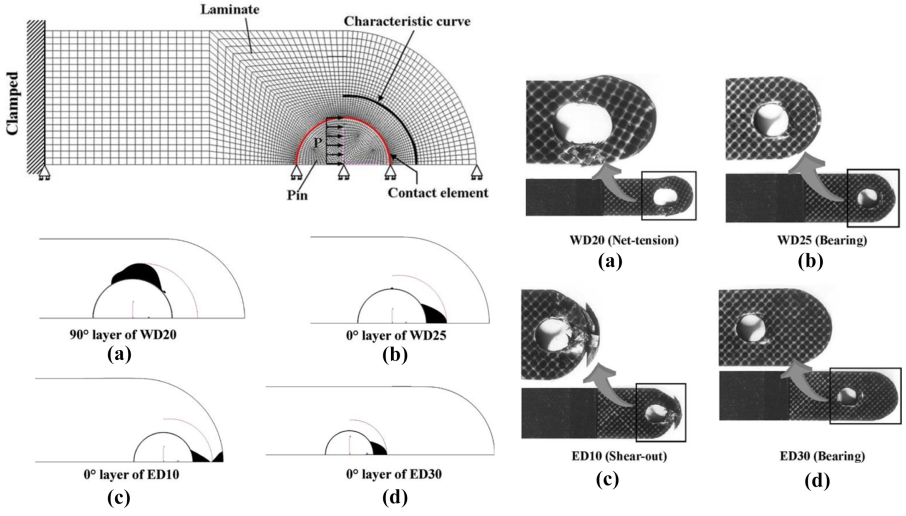
Figure 4.
Prediction method of static strength in composite bolted joints. (a) Strength envelope method, (b) Feature size method and (c) Progressive damage analysis theory

Here, R_t and R_c are the tensile feature size and compressive feature size, respectively, and r_0 is the hole radius, θ is the clockwise rotation angle of the longitudinal extrusion plane for composite materials.

Compared to the strength envelope method, the feature size method increases the judgment of failure modes and enhances its guidance for the design and analysis of bolted joint structures. However, this method is still an empirical method dominated by experimental data, without considering the influence of important variables such as geometric parameters and stacks order. In actual aircraft design and manufacturing, there are also significant differences in the stacked design parameters of composite materials of the same brand and obtaining characteristic dimensions through experiments under each operating condition requires significant time and cost. In recent years, researchers have also proposed some methods for coupling with the progressive damage analysis models to quickly and low-cost determine feature sizes, greatly reducing the cost of feature size testing under different operating conditions. Kweon *et al.* (2004) combined numerical simulation methods to give a new definition of feature size, which can obtain feature size parameters without experiments, as shown in Figure 5.

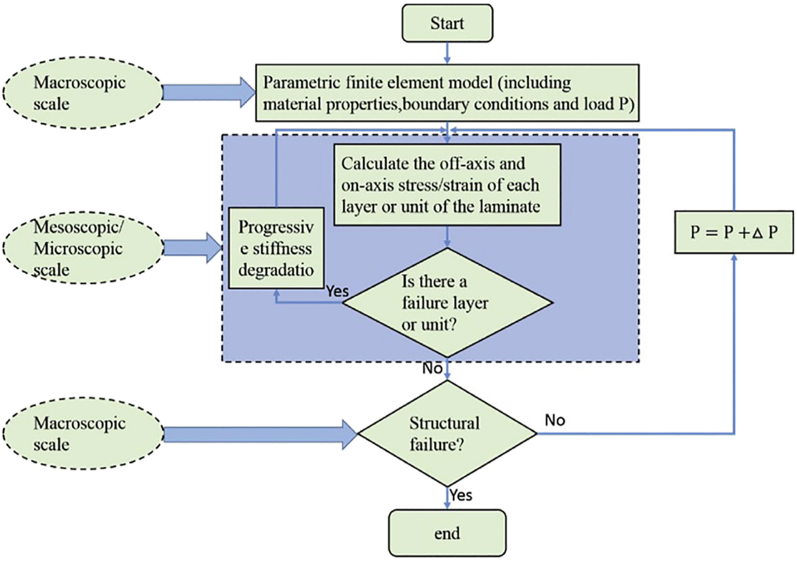
The progressive damage theory is currently the main tool for analyzing and studying the failure of composite/metal bolted joints (Chen *et al.*, 2019). It can perform stress analysis and failure prediction and fully consider the effects of stacked parameters and size parameters, reducing substantial mechanical tests. Especially with the development of composite material specific numerical simulation technology and the increasing abundance of hardware computing resources in recent years, numerical simulation models based on the progressive damage methods have gradually become the mainstream method for composite material failure analysis, as shown in Figure 6 (Zhang *et al.*, 2019; Rubiella *et al.*, 2018).

The progressive damage failure analysis mainly includes three parts: stress analysis model, failure criteria and performance degradation scheme. The stress analysis model is mainly implemented using various numerical simulation platforms for stress-strain calculations based on the constitutive relationship of composite materials. In the early



Source(s): Kweon *et al.* (2004)

Figure 5.
The method to determine the characteristic lengths of composite joints without testing



Source(s): Zhang *et al.* (2019)

Figure 6.
Flow chart of progressive failure analysis of composite

days, due to the limitations of finite element tools and computational resources, research often used the two-dimensional finite element methods for stress analysis. Currently, researchers mainly use the three-dimensional finite element models for stress analysis. Compared to the two-dimensional finite element model, the three-dimensional model can fully consider the influence of many parameters such as stacked scheme and preload.

The selection and implementation of failure criteria are the core of the progressive damage analysis methods, which determine whether the material failure state under a certain load can be correctly judged. CFRP stacks are a typical material with anisotropic mechanical properties, with complex failure modes. Existing failure theories mainly include the macroscopic phenomenological theory, microscopic damage theory and cross scale theory. Among them, the macroscopic phenomenological theory is the most widely used theory in engineering. The loading of composite materials under static strength can be divided into two stages. The first stage is the elastic stage, where there is no loss. The material exhibits linear elastic mechanical properties (Shen and Hu, 2006) and damage occurs when the load exceeds its strength. The failure criteria are used to determine the endpoint of the linear elastic stage and existing macroscopic failure theories are divided into two categories: phenomenological failure criteria independent of failure modes and physical failure criteria related to failure modes. The phenomenological failure criterion, which is independent of the failure mode, only judges whether the material has failed or not and does not determine the form of material failure. This type of failure criterion includes the maximum stress criterion, maximum strain criterion, Tsai-Hill criterion, Hoffman criterion and Tsai-Wu criterion. The physical failure criteria related to failure modes will determine the failure mode. Common failure modes include: matrix tensile failure, matrix extrusion failure, fiber tensile failure, fiber extrusion failure, fiber matrix shear failure, interlayer tensile failure and interlayer shear failure. This type of failure criterion includes Hashin criterion, Chang-Chang criterion, Puck criterion, Pinho criterion, LaRC series criterion, etc. Scholars at home and abroad have conducted extensive theoretical and applied research based on the theory of progressive damage analysis. For example, Sun (2018) established a finite element model based on the Abaqus platform and studied the transformation of failure modes for composite bolted joints structures with different apertures, as shown in Figure 7.

In summary, scholars currently use the methods such as strength envelope method, feature size method and the progressive damage analysis theory to conduct failure prediction and analysis of composite material strength in the research of the static strength failure theory of composite/metal stacks bolted joint structures. Meanwhile, scholars have conducted experimental verification on the static strength failure forms of composite/metal stacks bolted joint structures with different forms and materials.

3. Fatigue failure of composite/metal bolted joints

Fatigue failure is another important failure mode in materials and structures, which is the failure that occurs under reciprocating cyclic loads. Fatigue performance, as an important mechanical performance in aircraft service, has received widespread attention. In recent years, extensive research has been conducted on the fatigue failure characteristics of composite/metal bolted joint structures with different forms and materials, as shown in Table 2. It can be seen that metal material fatigue failure is the most important form of failure.

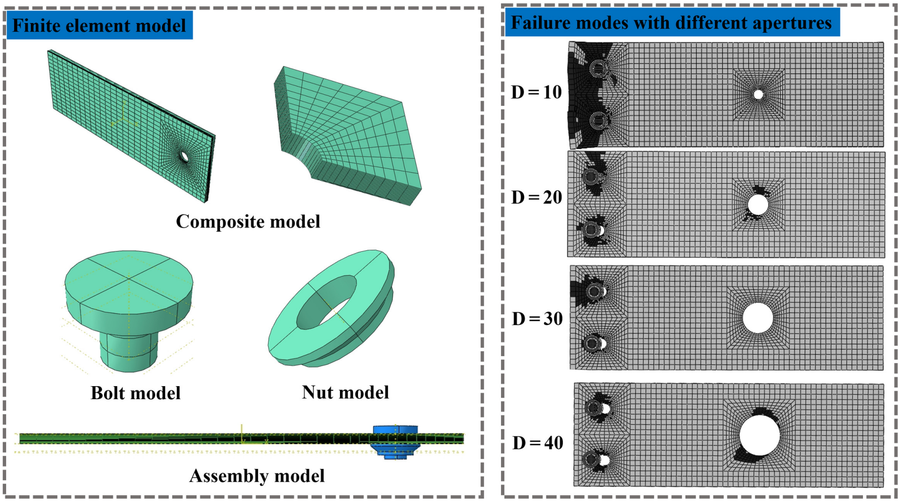


Figure 7.
Finite element prediction of failure modes in bolted connection structures of composite materials with different apertures

Source(s): Sun (2018)

Table 2.
Fatigue failure mode of composite/metal bolted joints

Researcher	Composite	Metal	Joint	Fatigue	Failure mode
Su (2013)	Hybrid textile 3.8 mm	Ti6Al4V 2 mm	Double nail single shear	Tensile fatigue $q = 0.7, R = 0.1$	Metal tensile fatigue failure
Ge (2015)	T800/X850 4.7 mm*2	Ti6Al4V 4.7 mm	Single nail double shear	Tensile fatigue $q > 0.6, R = 0.1$	Metal tensile fatigue failure
An *et al.* (2021)	T700 4.7 mm	Ti6Al4V 4.7 mm	Multiple nails and single shear	Tensile fatigue $q = 0.67, R = 0.1$	Metal tensile fatigue failure
Jiang *et al.* (2017)	T300 2.5 mm	5682-T6 1.8 mm	Single nail and single shear	Tensile fatigue $q > 0.55, R = 0.1$	Metal tensile fatigue failure
Shan *et al.* (2020)	T800/X850 2.292 mm	7050-T651 3.3 mm	Double nails and double shear	Tensile fatigue $q > 0.7, R = 0.1$	Corner failure of composite and metal tensile fatigue failure

Source(s): Table created by authors

Compared with the summary analysis of static strength failure, there is a significant difference between fatigue failure mode and static strength failure mode. Composite material failure is the main failure mode in static strength failure and tensile fatigue failure of metal is the main failure form in fatigue failure. This phenomenon indicates that composite materials have a large damage tolerance and significantly better fatigue performance than metal materials.

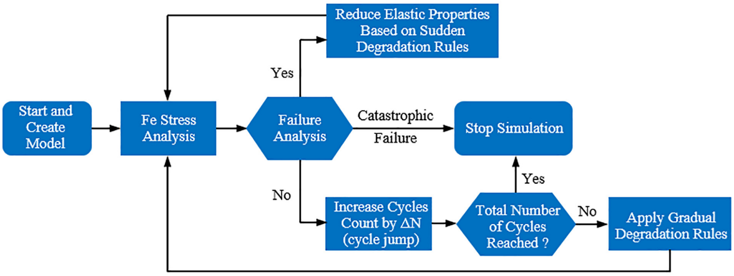
The research on fatigue life prediction of metal materials is relatively mature and widely applied in engineering. Currently, it is mainly divided into two directions: life assessment methods under constant amplitude load and damage accumulation theory. The life assessment methods under constant amplitude load are mainly used to determine life under fixed load and can also provide damage basis for life calculation in complex load spectra. The main methods include the Coffin–Manso model, Paris formula, etc (Sun *et al.*, 2017). The damage accumulation method provides a basis for the analysis of complex loads, assuming that complex fatigue loads are composed of numerous constant amplitude loads and damage is calculated and accumulated separately. The main theoretical methods include the Miner linear fatigue accumulation damage model, bilinear accumulation damage model, Henry fatigue injury accumulation model, etc (Yuan and Li, 2005).

The fatigue life prediction method for composite material bolted joints is a focus of research on the fatigue performance of composite/metal stacks bolted joints. It mainly includes methods such as the S–N curve method, prediction method based on residual strength and residual stiffness degradation law and progressive damage analysis method based on physical failure mechanism of composite materials. The S–N curve method is a semi empirical model that can obtain a direct relationship between stress levels and fatigue life through a large number of experiments, without studying the failure mechanism of materials. Composite materials are different from metal materials, as they are a typical anisotropic material that is severely affected by the stacked parameters. The widely used the S–N curve method in the field of metal materials is difficult to achieve good prediction results in the life analysis of composite materials. The prediction method established based on the degradation law of residual strength and residual stiffness is essentially an experimental method, only transitioning from direct prediction of the S–N curve to indirect prediction of residual performance after a certain lifespan.

The progressive fatigue damage model (PFDM) for composite materials is a rapidly developing new method in the field of fatigue performance analysis and prediction in recent years. Shokrieh and Lessard (2000a, b) first proposed a framework for the progressive damage analysis and prediction of composite material fatigue in 2000, which had a profound impact on the analysis and prediction of composite material fatigue failure. This framework established a complete fatigue failure analysis and prediction process for composite materials and their components, as shown in Figure 8. This framework includes stress analysis, fatigue failure criteria, material performance degradation and sudden degradation schemes, and can be achieved through secondary development of FEM software and material models. On the basis of the Skokrieh classic framework, researchers have made numerous improvements and changes to meet different analysis needs. For example, Shan *et al.* (2018) achieved effective prediction of fatigue life of composite materials under humid and thermal conditions by coupling failure criteria and damage evolution schemes in the model, as shown in Figure 9.

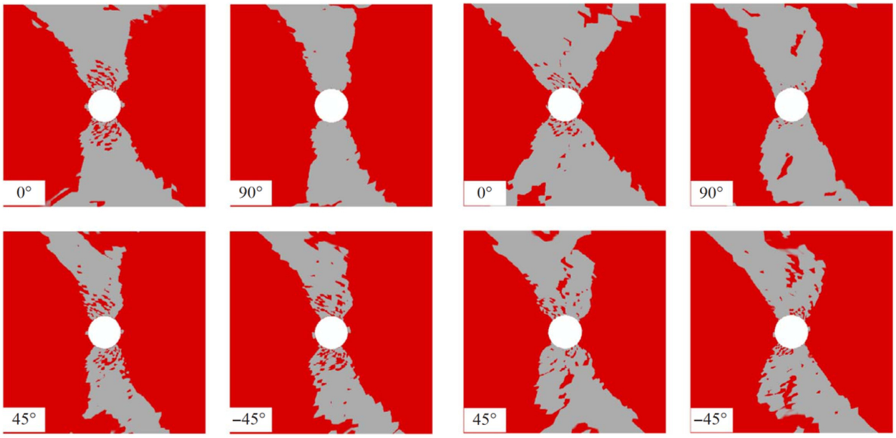
There is relatively little research on the fatigue life of bolted joint structures of composite/metal in the existing studies. The failure modes of connection structure, as a multivariate mechanical system, are closely related to the failure modes of various components. Shan *et al.* (2020, 2022) proposed the competitive failure theory to comprehensively consider the fatigue performance of composite material connecting plates, metal connecting plates and bolts, as shown in Figure 10. Su (2013) also adopted a similar method in his research.

Based on the comprehensive experimental and theoretical research, the existing studies have shown that the fatigue performance of composite/metal bolted joints is related to multiple factors, mainly including structural parameters, material design, pre-tightening



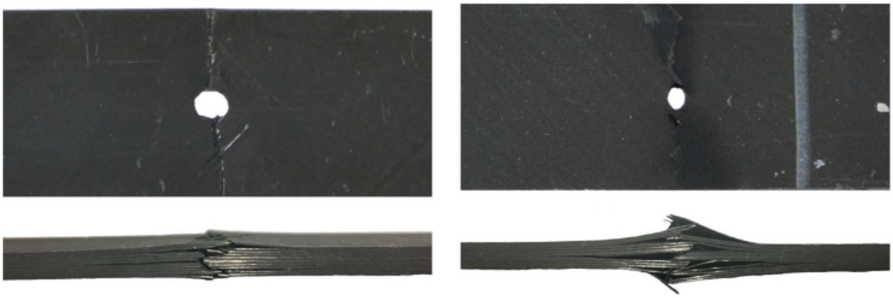
Source(s): Shokrieh and Lessard (2000a, b)

Figure 8.
Composite fatigue progressive damage analysis framework



$\sigma_{\max} = 344\text{MPa}, R = 10$
(a)

$\sigma_{\max} = 325\text{MPa}, R = 10$
(b)

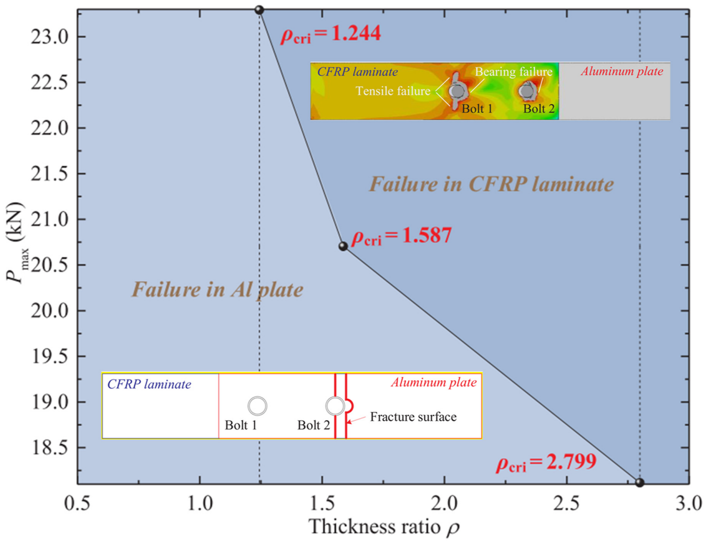


$\sigma_{\max} = 344\text{MPa}, R = 10$
(c)

$\sigma_{\max} = 325\text{MPa}, R = 10$
(d)

Source(s): Shan *et al.* (2018)

Figure 9.
Prediction of fatigue life of composite materials under wet and hot conditions using coupled failure criteria and damage evolution schemes



Source(s): Shan *et al.* (2020)

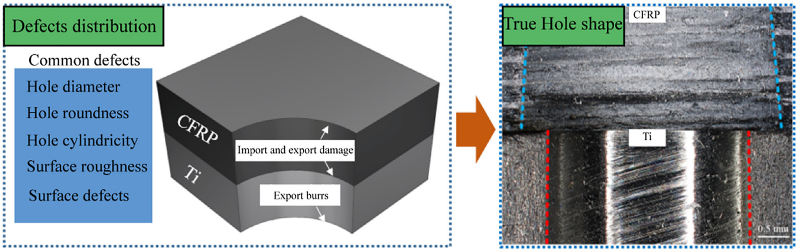
Figure 10. The failure mode diagram of the CFRP-aluminum bolted joint

torque and assembly accuracy. Among them, aperture creation and precision control are important parameters that run through the design and manufacturing process of composite/metal stacks bolted joints, and their results directly determine the quality and efficiency requirements of manufacturing. However, current research is mainly based on ideal assembly with no gaps or uniform gaps in the thickness direction, without considering the hole-forming defects shape characteristics generated by stacked drilling.

4. The influence of drilling accuracy on mechanical properties of composite/metal stacks

4.1 Typical defects and quality evaluation of composite/metal stacks structure drilling

The difference in material properties between composite and metals leads to significant differences in their hole-forming defects. The anisotropy and stacked material composition characteristics of composite materials make the hole-forming quality characteristics significantly different from metal materials. Taking carbon fiber reinforced polymer/titanium alloys (CFRP/Ti) as an example, as shown in Figure 11, the evaluation of hole-making quality mainly focuses on geometric errors, thermal damage and physical damage (Yan *et al.*, 2022; Pan *et al.*, 2022; Xu *et al.*, 2022). The geometric aspects mainly include hole



Source(s): Figure created by authors

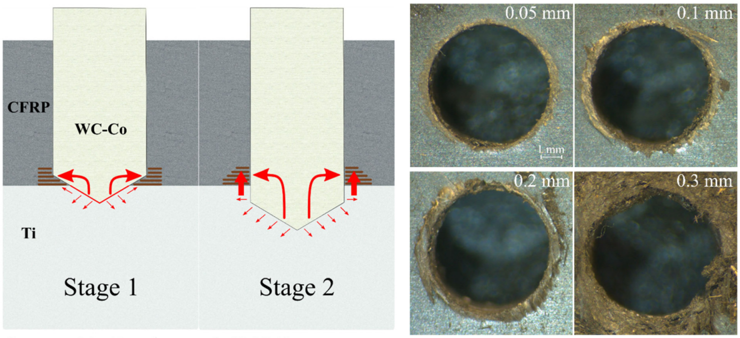
Figure 11. Hole-making induced damage distribution of CFRP/Ti stacks

size, roundness, cylindricity, roughness and burr height, while the physical evaluation mainly focuses on the study of composite material stacks (Zhang *et al.*, 2020a, b).

The micro damage mechanisms of the CFRP layer mainly include matrix fracture, fiber fracture and interlayer delamination. Composite materials exhibit almost no plasticity at the macro-level, but at the micro-level, due to the low hardness of the resin matrix, hole-forming damage is prone to occur. The main types of damage that CFRP layers are concerned about are geometric errors, thermal damage and delamination damage at the entrance and exit of holes. The most prominent machining quality issue in the CFRP to Ti processing sequence is the severe error in the hole size of the CFRP layer. The main reason is that the high temperature and high hardness chips generated during the cutting of the lower titanium alloy continue to scratch the CFRP hole, leading to serious damage to the hole size characteristics. Delamination damage is the most serious processing quality issue of the CFRP layer in the Ti to CFRP processing sequence, mainly due to insufficient support stiffness at the outlet when CFRP is used as the lower layer material. Delamination damage is a serious irreversible processing damage and the cause of a large number of unqualified composite material components in the aviation industry. Its causes are considered to be lower interlayer strength and insufficient bottom support.

The interface between CFRP and Ti is the area where machining defects are most likely to occur, especially in the unstable cutting state with gap, which can easily induce serious machining damage. When the tool cuts at the interface, the cutting edge simultaneously cuts both composite and metal materials, and the tool is in an unstable cutting state. Generally speaking, the damage at the interface mainly includes mechanical scratches, discoloration caused by high temperature, fiber extraction and wire drawing. The gap between stacked holes is considered an important factor affecting the interface quality of stacked hole-making, including assembly gap and deformation gap caused by axial force. The increase in absolute gap (including assembly gap and axial force induced gap) can lead to more severe interface mechanical and thermal damage. Pardo *et al.* (2021) simulated the effect of assembly gaps on stacked interface damage using gaskets of different thicknesses. The research results showed that interface damage is mainly caused by titanium alloy chips entering the stacked interface and the larger the gap, the larger the size of titanium alloy chips entering the gap, resulting in more severe interface processing damage, as shown in Figure 12.

Titanium alloy is a typical elastic-plastic metal material, which is removed through elastic-plastic shear and deformation (Peng *et al.*, 2023). The surface quality of the titanium alloy layer has been greatly improved compared to composite materials. Titanium alloy has a small thermal conductivity of about 15.24 W/(m.K), and the cutting heat generated during cutting is



Source(s): Proda *et al.* (2021)

Figure 12.
CFRP interface damage for different interlayer gaps

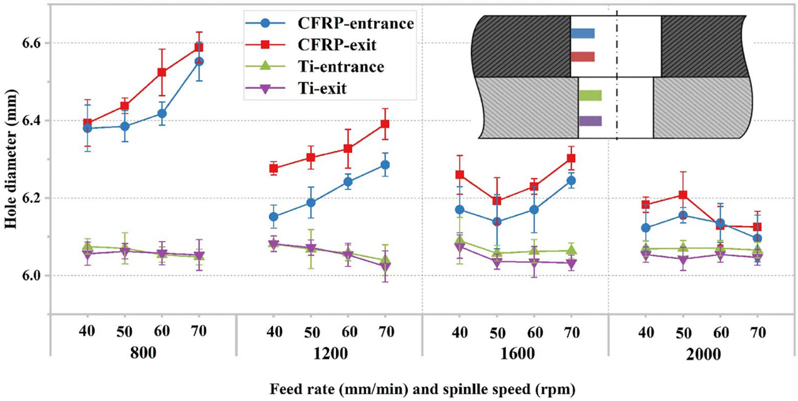
prone to accumulate and generate higher cutting temperatures, leading to hole size deviation and thermal damage. The quality evaluation of titanium alloy layers in hole-making mainly focuses on indicators such as aperture accuracy, roughness and export burr height. Among them, the height of export burrs has been widely studied in literature. Additionally, due to significant differences in cutting temperature and material properties, there is a significant difference in hole size between the titanium alloy layer and the CFRP layer.

In the mass production of CFRP/Ti stacked connection structures, the aperture accuracy feature (diameter at the inlet and outlet of each layer) is one of the most important evaluation indicators, which directly affects assembly accuracy and long-term service performance. The CFRP/Ti stacked connection structure exhibits significant stepped hole phenomenon under typical processes (Qi *et al.*, 2021), where the average hole size of the composite material layer is significantly larger than that of the titanium alloy layer, as shown in Figure 13. At the same time, there is a significant phenomenon of conical holes in the composite material layer. The phenomenon of stepped holes is widely present in the research of CFRP/Ti hole-making processes, and the hole size and shape have also been extensively studied.

4.2 The correlation mechanism between the assembly accuracy and the mechanical properties of composite/metal stacks

The feature of hole size is the most important indicator in the quality evaluation of CFRP/Ti stacked hole-making. It directly affects the assembly state of nail holes in bolted joints, thereby affecting the mechanical properties of the connection structure. Domestic and foreign scholars have conducted a small amount of research on the correlation mechanism between hole-making accuracy and connection performance.

McCarthy is the earliest and most widely studied scholar on the mechanism of the influence of fitting accuracy on the connection performance in composite material bolted joints. In terms of testing, McCarthy *et al.* (2002) and Lawlor *et al.* (2002) conducted mechanical performance tests on single nail and single shear bolted joint structures. In the tests, extrusion failure was the initial failure mode and bolt failure was the final failure mode. The results showed that an increase in assembly gap would lead to a decrease in the load-bearing stiffness and an increase in ultimate displacement of the connection structure. The relationship between gap and ultimate strength first increased and then decreased, at the same time, the study also pointed out that an increase in gap can lead to a certain delay effect



Source(s): Qi *et al.* (2021)

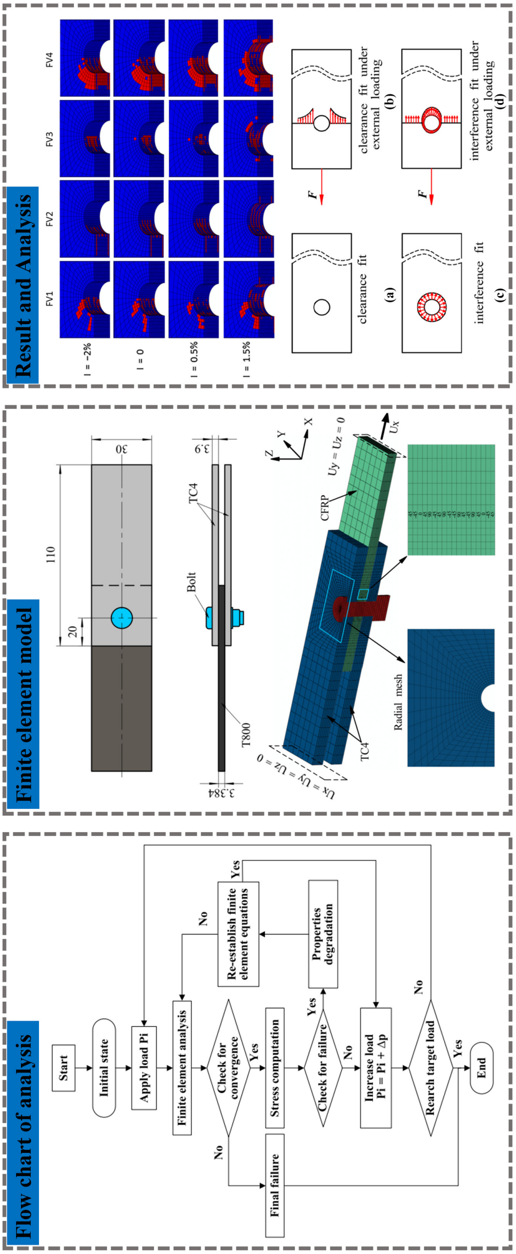
Figure 13.
Evolution of diameter of entrance and exit hole in CFRP and titanium alloy versus drilling parameters

in load-loading, which has an important impact on multi-nail connection structures. In terms of numerical simulation, McCarthy *et al.* (2005) and McCarthy and McCarthy (2005) for the first time introduced a three-dimensional finite element analysis method based on progressive damage into the study of the effect of gap on the performance of bolted joints. In the study, a finite element model of composite material bolted joints was established using MSC software. The model demonstrated high accuracy in simulating stress, strain and secondary bending effects of single shear structures. Different gaps were simulated based on the model, the result indicate that an increase in gap will exacerbate the secondary bending effect and the uneven distribution of stress and strain in the thickness direction. However, the series of studies mainly focused on the static strength of composite/composite connection structures, without involving the static strength failure and fatigue failure of composite/metal connection structures.

Cao *et al.* (2018) studied the effect of aperture accuracy on connection performance in CFRP/Ti single nail double shear bolted joints through a combination of experimental and simulation methods. In the study, a three-dimensional finite element analysis model based on the improved Hashin failure criterion and Tan degradation criterion was established using the Abaqus platform, and experimental verification was conducted. The study found that the connection strength decreased with increasing gap, and the fatigue life also decreased with increasing gap, as shown in Figure 14. At the same time, the study also pointed out that there is a certain correlation between the static strength failure mode of composite materials and the hole-making process and accuracy. Zhong (2020) studied the effect of hole-making accuracy on the static strength performance of composite/composite single nail single shear bolted joints through the experimental and simulation methods. The results showed that stress concentration was more significant under larger gaps, leading to a decrease in connection strength, as shown in Figure 15.

Zou *et al.* (2023) show that the influence of hole-making process and parameters on the hole-making accuracy of CFRP/Ti stacked structure is mainly reflected in the control of titanium alloy chip size and morphology. The increase in feed rate improves the cross-sectional size of titanium alloy chips and significantly deteriorates the hole-making accuracy of the stacked structure. In conventional drilling, the chips are longer, and the introduction of chip breaking technology can control the length of the chips. The pecking drilling and reaming process (PDR) and low frequency vibration assisted drilling and reaming process (LFVADR) can effectively reduce chip length and improve hole-making accuracy compared to conventional drilling and reaming (CDR). At the same time, it was found that the hole-making process did not change the static strength tensile failure form of the connection structure, but it would have an impact on the bearing stiffness, effective load and ultimate load during the loading process. The maximum difference in ultimate strength was 5.4%, and the maximum difference in loading stiffness was 10.7%. A multidimensional connection hole-making quality evaluation method was proposed that comprehensively considers machining efficiency, tool cost, aperture accuracy and connection mechanical performance. It was found that the combination of low frequency vibration assisted hole-making and reaming hole-making process can achieve high hole-making accuracy while maintaining high machining efficiency, and is suitable for mass production of aviation structural components, as shown in Figure 16.

Scholars have also studied the impact of fitting accuracy in aspects such as the hole-making perpendicularity error on the connection performance. Gao *et al.* (2017) studied the effect of 0–4° perpendicularity error on the performance of composite material single nail single shear bolted joint through the experimental methods. The results showed that perpendicularity error has an impact on ultimate strength, stiffness and 2% bearing strength. The main reason is that the presence of perpendicularity error leads to changes in stress concentration, thereby changing the initiation and development of damage. The 180° tilt direction has greater chord stiffness than the 0° tilt direction.



Source(s): Cao *et al.* (2018)

Figure 14.
The influence of aperture accuracy on the performance of CFRP/Ti single nail double shear bolted joints

From the above research, it can be seen that the verticality and aperture accuracy of composite/metal stacked hole-making have a significant impact on the connection

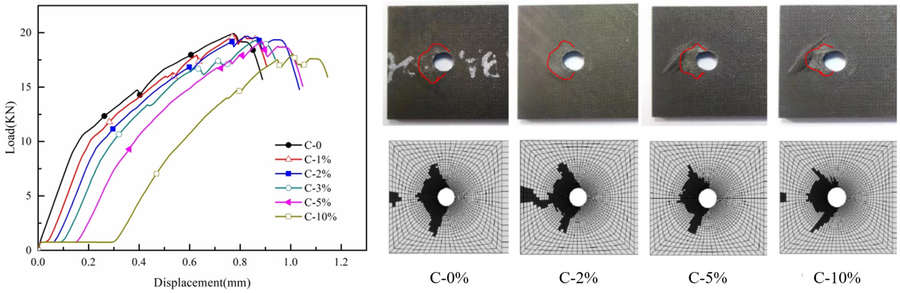


Figure 15. The influence of clearance on the static strength and damage of composite/composite single nail single shear bolt connections joints

Source(s): Zhong (2020)

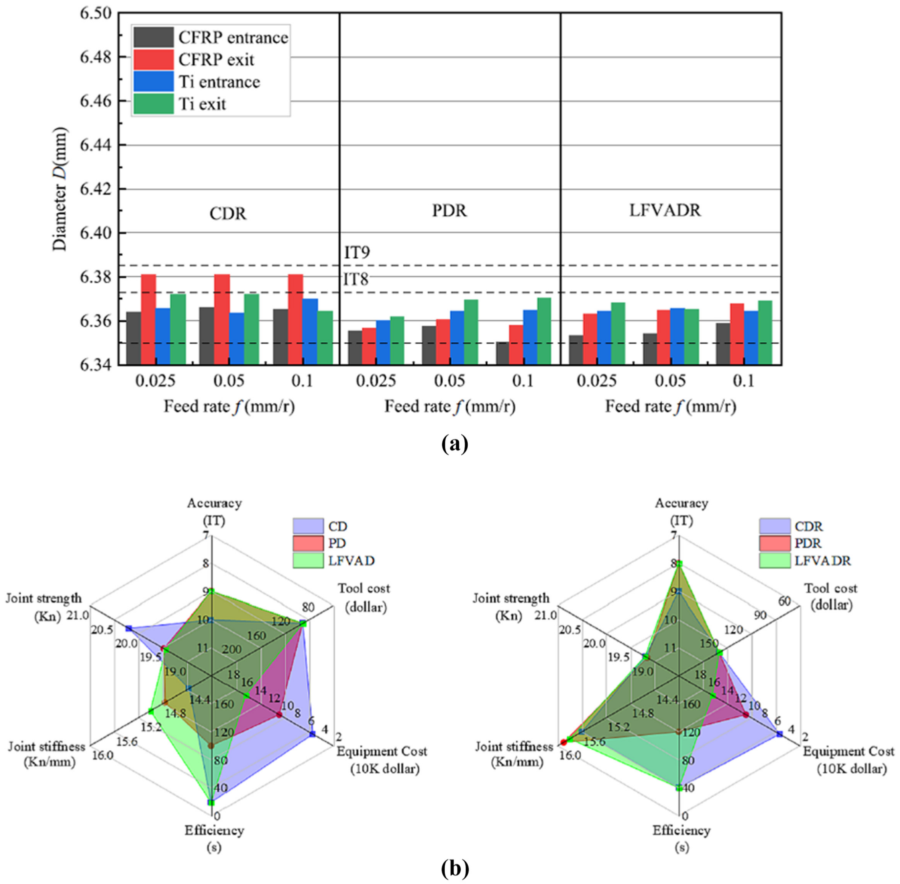


Figure 16. (a) Hole size characteristic and (b) multiple criteria evaluation of under different process

Source(s): Zou *et al.* (2023)

performance, and the mechanical responses affected mainly include ultimate strength, bearing stiffness, secondary bending effect and fatigue life. The hole-making process has a significant impact on the aperture accuracy of composite/metal stacked holes. The use of low frequency vibration assisted hole-making and other processes can effectively reduce chip length, improve the hole-making accuracy of composite materials and improve connection strength and fatigue life. It is worth noting that the service performance evaluation of composite/metal stacked structures is currently limited to the static strength and fatigue failure tests of sample-level components and needs to be improved and validated in higher complexity structures. At the same time, it needs to be extended to mechanical performance research in more environments and more complex forms of external loads.

5. Conclusions and prospects

Composite/metal bolted joint structures are widely used in the important load-bearing parts of advanced aircraft, and the position of composite/metal bolted joint is also a weak link in the overall structure. The mechanical performance of the connection structure directly affects the overall structural safety of the aircraft. Many scholars actively explore the theoretical prediction methods for static strength and fatigue failure of composite/metal bolted joints as well as the impact of hole-making accuracy on their mechanical properties and have achieved some results. Based on the literature review, the following conclusions have been drawn:

In terms of theoretical research on the static strength failure of composite/metal stacked bolted joint structures, the feature size method and strength envelope method lack consideration of geometric parameters and ply order variables. However, the progressive damage analysis method can accurately analyze and predict the static strength failure of composite/metal stacked bolted joint structures by establishing a stress analysis model combined with composite material performance degradation schemes and failure criteria.

There is a significant difference between the fatigue failure mode and static strength failure mode of composite/metal bolted joints. Composite material failure is the main failure mode in static strength failure, while tensile fatigue failure of metal is the main failure form in fatigue failure. The use of mature metal material fatigue cumulative damage models and composite material fatigue progressive damage analysis methods can effectively predict the fatigue of composite/metal bolted joints.

Geometric errors, scratches and delamination of composite material aperture are the typical defect forms in the hole-making process of composite/metal stacked structures. The geometric errors such as aperture accuracy and hole perpendicularity have the most significant impact on the connection performance and their mechanical responses mainly include ultimate strength, bearing stiffness, secondary bending effect and fatigue life. The quality and accuracy of composite/metal stacked hole-making are greatly influenced by hole-making process and parameters. The use of low-frequency vibration assisted hole-making and other processes can effectively reduce the chip length, improve the composite material hole-making accuracy and improve the connection strength and fatigue life.

Aperture creation and precision control are important parameters in the manufacturing process of composite/metal stacked bolted joints, and their results directly determine the quality and efficiency requirements of manufacturing. However, current research on the theoretical prediction of the mechanical properties of composite/metal bolted joints is mainly based on ideal fits with no gaps or uniform gaps in the thickness direction, without considering the hole shape characteristics generated by stacked drilling. At the same time, the service performance evaluation of composite/metal stacked bolted joints structures is currently limited to the static strength and fatigue failure tests of sample-level components and needs to be improved and verified in higher complexity structures. At the same time, it also needs to be extended to the mechanical performance research under more complex forms of the external loads in more environments.

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